

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE  
BEFORE THE BOARD OF PATENT APPEALS AND INTERFERENCES

Firm Named

Inventor : Yukiko Kubota

Appln. No.: 10/650,302

Filed : August 28, 2003

For : HIGH MOMENT DIRECTIONALLY  
TEXTURED SOFT MAGNETIC  
UNDERLAYER IN A MAGNETIC  
STORAGE MEDIUM

Docket No.: S01.12-0965/STL 11036.00

Appeal No. \_\_\_\_\_

Group Art Unit: 1773

Examiner:

Holly C. Rickman

**TRANSMITTAL OF APPEAL BRIEF  
(PATENT APPLICATION - 37 C.F.R. §41.37)**

Mail Stop Appeal Brief - Patents  
Commissioner for Patents  
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19 DAY OF September, 2005.  
  
PATENT ATTORNEY

Sir:

Transmitted herewith is the Appeal Brief in this  
application with respect to the Notice of Appeal filed on August 2,  
2005.

FEE STATUS

[---] Small entity status under 37 C.F.R. §§ 1.9 and 1.27  
is established by a verified statement---

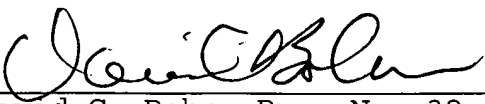
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Respectfully submitted,

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## BRIEF FOR APPELLANT

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*[Signature]*

PATENT ATTORNEY

Sir:

This is an appeal from an Office Action dated June 8, 2005 in which claims 1-6, 8-22 and 25-28 were finally rejected.

### REAL PARTY IN INTEREST

Seagate Technology LLC, a limited liability company organized under the laws of the state of Delaware, and having offices at 920 Disc Drive, Scotts Valley, California 95066 has acquired the entire right, title and interest in and to the invention, the application, and any and all patents to be obtained therefor, as set forth in the Assignment filed with the patent application and recorded on Reel 014483, frame 0909.

### RELATED APPEALS AND INTERFERENCES

There are no known related appeals or interferences which will directly affect or be directly affected by or have a bearing on the Board's decision in this appeal.

### STATUS OF THE CLAIMS

I. Total number of claims in the application.

Claims in the application are:

1-31

II. Status of all the claims.

A.	Claims cancelled:	none
B.	Claims withdrawn but not cancelled:	29-33
C.	Claims pending:	1-33
D.	Claims allowed:	none
E.	Claims rejected:	1-6, 8-22, 25-28
F.	Claims Objected to:	7, 23-24

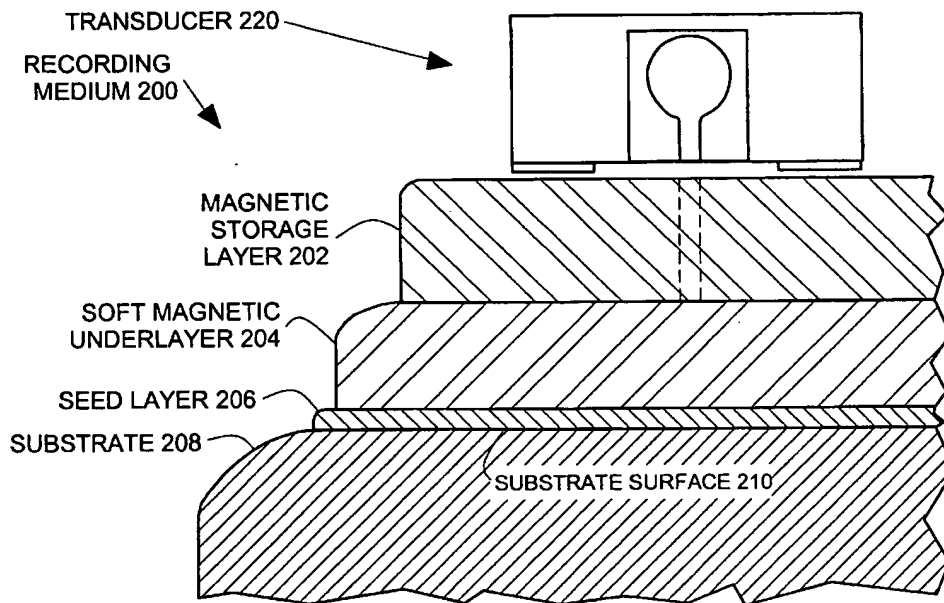
III. Claims on appeal

The claims on appeal are: 1-6, 8-22, 25-28

STATUS OF AMENDMENTS

A Response after Final was filed on May 16, 2005. In a June 8, 2005 Advisory Action before filing an Appeal Brief, the Response after Final was entered for purposes of Appeal.

SUMMARY OF CLAIMED SUBJECT MATTER

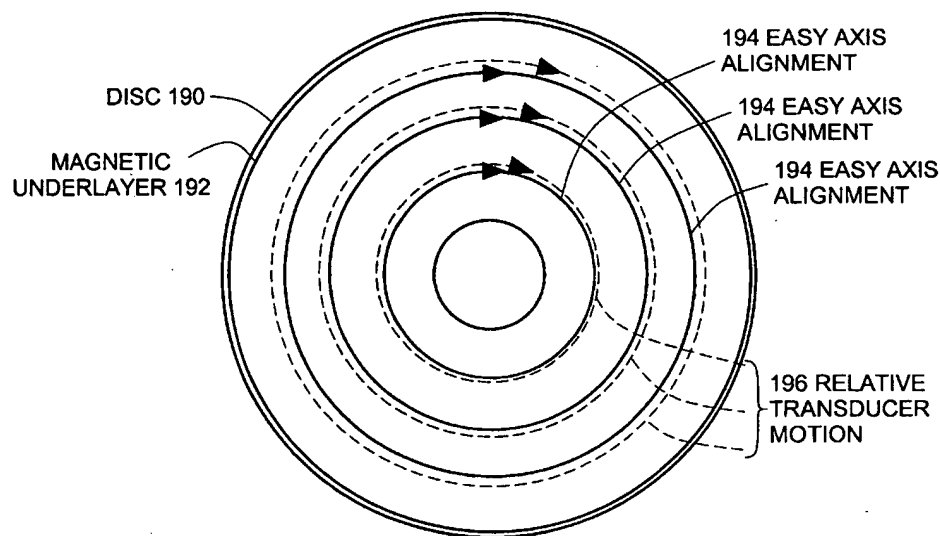


As illustrated in cross-section above and in FIG. 5 of

the specification, a magnetic recording medium 200 comprises a substrate 208 that has a substrate surface 210. A seed layer 206 is disposed on the substrate surface 210.

A soft magnetic underlayer 204 is disposed on the seed layer 206. The soft magnetic underlayer 204 has a texture that provides a magnetic easy axis alignment parallel to a line of relative motion of a transducer 220. A magnetic storage layer 202 is disposed on the soft magnetic underlayer 204. (FIG. 5 and specification, page 10, line 16 through page 12, line 12.)

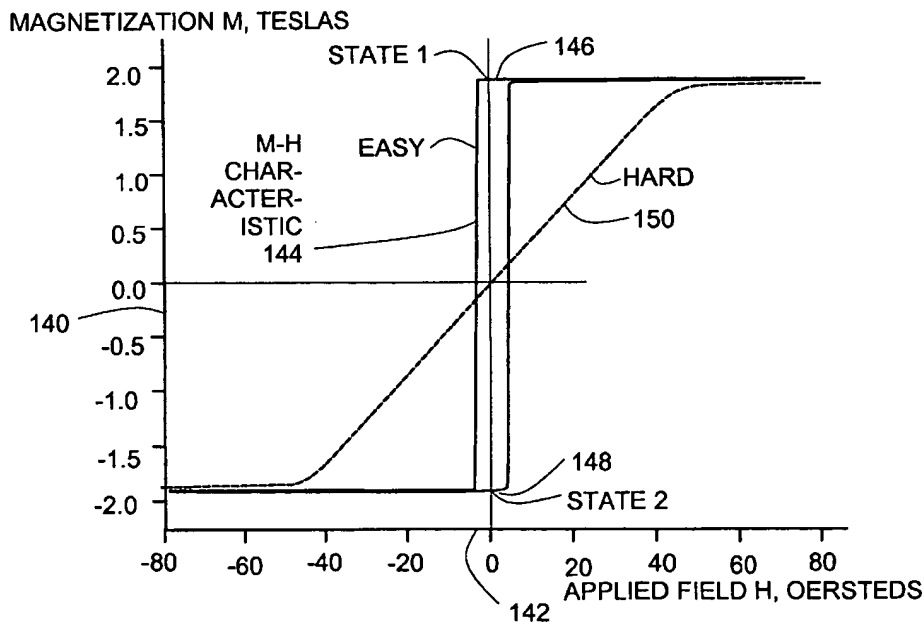
The applied field (magnetic flux) from a transducer (write head) flows through a closed magnetic circuit from a narrower single pole on the transducer head, through a recording element of the magnetic storage layer 202, through the soft underlayer, and then back to a wider return pole on the transducer head. (Specification page 5, lines 19-22).



As illustrated above and in FIG. 4 of the specification, a disc 190 includes a magnetic underlayer 192 that has a circumferential easy axis alignment (solid lines 194) that is parallel to circumferential relative motion (dashed lines 196) of a transducer. (FIG. 4 and specification, page 9, line 3 through

page 10 line 2). Circumferential easy axis alignment comprises a means for texturing a soft magnetic underlayer to provide alignment with a circumferential line of relative transducer motion in a disc drive.

The soft magnetic underlayer 204 comprises a magnetic material that has a texture and that has a magnetic moment that is larger than 1.7 teslas. (Specification page 4, lines 27-29.)



As shown above and in FIG. 2 of the specification, a static M-H characteristic 144 along the easy axis alignment is illustrated as a graph of magnetization M in teslas (axis 140) of the soft underlayer material as a function of an applied magnetic field H in oersteds (axis 142). The applied magnetic field is generated by the transducer 220 (FIG. 5). The M-H characteristic 144 includes saturation states STATE 1 and STATE 2 that correspond with the magnetic moment of the soft underlayer material. In the example of FIG. 2, a magnetic moment of approximately 1.9 teslas is shown. Between the saturation states, the soft underlayer material exhibits a high magnetic permeability, as illustrated by

steep vertical slopes of the static M-H characteristics. (FIG. 2 and specification page 7, line 12 through page 8, line 2.)

Use of a conventional soft underlayer with relatively low magnetic moment in the range of less than 1.7 teslas leads to a requirement for an excessively thick soft underlayer in a thickness range of about 200-400 nanometers thickness. The large thickness induces a large surface roughness which interferes with small transducer-to-media spacing requirements for high density recording.

Applicants have found that treating the soft underlayer to increase its magnetic moment to be larger than 1.7 teslas along the easy axis, and preferably larger than 2.0 teslas improves the performance of the soft underlayer material such that its thickness can be reduced to less than 200 nanometers, thus avoiding excessive interference with small transducer-media spacings. (Specification, page 10, lines 5-15).

#### GROUND OF REJECTION TO BE REVIEWED ON APPEAL

In the Office Action of April 4, 2005, the Examiner rejected Claims 1-6, 8-22 and 25-28 under 35 USC 103(a) over Carey et al. US 2003/0022023 in view of Shimizu et al. US 2002/0004148.

The Examiner argued that "With respect to the claim limitation directed to a magnetic moment greater than 1.7 T, it is the Examiner's contention that the CoFe soft magnetic layers taught by Carey et al. inherently satisfy this limitation by virtue of the fact that magnetic moment is a material property and Applicants teach using the same material."

In reply to applicant's Reply after Final (May 16, 2005), the Examiner issued a subsequent Office Action of June 8, 2005 in which the Examiner argued that "The Examiner maintains that it is reasonable to believe that the FeCo alloy taught by Carey et al. would inherently have a magnetic moment of 'at least 2.4 Teslas' in view of Applicant's specification."

In the Office Action of June 8, 2005, the Examiner also argued that "With regard to Applicant's statement that the examiner has not provided support for the assertion that magnetic moment does not depend on annealing conditions, Applicant is reminded that it has been held that where claimed and prior art products are identical, or are produced by identical or substantially identical processes, the burden of proof is shifted to the applicant to show that prior art products do not necessarily or inherently possess characteristics of claimed products where the rejection is based on inherency under 35 USC 102 or on prima facie obviousness under 35 USC 103, jointly or alternatively. *In re Best, Bolton, and Shaw*, 195 USPQ 430 (CCPA 1977) Thus, it is Applicant's burden to present probative evidence that the prior art would not inherently meet the claim limitations."

#### ARGUMENTS

##### I.

Magnetic moment along an easy axis is not an intrinsic or inherent property of a particular composition of a magnetic material. For a particular composition of magnetic material, magnetic moment along an easy axis is not a fixed value, but can be varied by magnetic annealing history of the particular composition of magnetic material.

When magnetic material (such as magnetic material in a soft underlayer) is subjected to a magnetic field of strength  $H$ , the magnetic field exerts a torque on magnetic domains in the magnetic material. The torque is a maximum when the axis of the domain is perpendicular to the magnetic field. As the magnetic field increases from zero, domains (in the magnetic material) change size and rotate in increasing amounts to align with the magnetic field. When substantially all of the magnetic domains subject to the magnetic field are aligned with the field, the

material is said to be in a completely magnetized in a saturation state. The complete magnetization of the material is referred to as the magnetic moment of the material. (McGraw-Hill Concise Encyclopedia of Science and Technology, Third Edition, Sybil P. Parker, Ed., page 1100, McGraw-Hill, Inc. 1994; Magnetic Disc Drive Technology, Kanu G. Ashar, pages 37-38, IEEE Press 1997.)

For a particular composition of soft magnetic material, the magnetic moment along the easy axis of the material depends on the combined thermal and magnetic history (magnetic annealing) of the material. For example, as shown in FIGS. 10.2(a), (b), (c) and (d) on page 360 of Introduction to Magnetic Materials, four different M-H characteristics are shown for the same 65% nickel (Ni), 35% iron (Fe) composition with different magnetic annealing histories. The alloy composition is the same for all the different M-H characteristics, but the thermal and magnetic history is different as described in the legend under FIG. 10.2. In FIG. 10.2(a), the material has a magnetic moment of about  $12 \times 10^3$  gauss (1.2 tesla). In FIG. 10.2(b), the material has a magnetic moment of about  $10 \times 10^3$  gauss (1.0 tesla). In FIG. 10.2(c), the material has a magnetic moment of about  $13.3 \times 10^3$  gauss (1.33 tesla). In FIG. 10.2(d), the alloy material is transversely magnetized during annealing and does not reach its maximum magnetic moment with an applied field of 3 oersteds.

The static M-H characteristics in Figures 10.2(a)-(d) are comparable to the static M-H characteristics in FIG. 2 in the application and have the same axes. The vertical (magnetization axis) in FIG. 2 is scaled in teslas, while the vertical (magnetization axis) in figures 10.2(a)-(d) is scaled in gauss. Horizontal axes in both figures are scaled in oersteds. A "tesla" (T) is an SI unit of magnetic flux density, a "gauss" (G) is a CGS unit of magnetic flux density, and one tesla (T) is equal to  $10^4$  gauss (G). An oersted is a CGS unit of magnetic field strength. (Chambers Dictionary of Science and Technology, Prof. Peter M. B.

Walker, Ed., pages 497, 805, 1157 Chambers Harrap Publishers Ltd., 1999.)

FIGS. 10.2(a), 10.2(b), 10.2(c), 10.2(d) demonstrate that magnetic moment is not an intrinsic (inherent) property of a particular material composition because the magnetic moment varies and depends on parameters other than the particular material composition. Magnetic moment along an easy axis depends on a magnetic and thermal history, and not only on material composition. (Introduction to Magnetic Materials, B. D. Cullity, pages 357-360, Addison-Wesley Publishing Company, Inc. 1972.)

The feature of increasing the magnetic moment along an easy axis of the soft magnetic underlayer to larger than 1.7 teslas, when taken in combination with the texture of the soft magnetic underlayer and other features of Claims 1-6, 8-22 and 25-28, patentably distinguishes the claimed invention from the prior art cited.

There is no teaching or suggestion in the prior art cited by the Examiner that the magnetic moment be raised to a level greater than 1.7 teslas in combination with a texture that provides a magnetic easy axis. The devices taught in the prior art cited by the Examiner do not inherently possess the claimed characteristic of a magnetic moment greater than 1.7 teslas in combination with a texture that provides a magnetic easy axis.

Even though two magnetic materials may have exactly the same chemical composition, the two magnetic materials can be physically different because the two materials have different texturing and different grain structures. The value of magnetic moment is not inherent to a particular chemical composition. The value of magnetic moment is a function of thermal magnetic history as well as texturing. In order for the Examiner to make a finding of inherency, the composition recited in the claims must be physically identical to a composition in the prior art. MPEP 2112.01 II. The composition recited in the claims has an easy axis

and the magnetic moment is greater than 1.7 teslas along the easy axis and is not physically identical to the compositions in the prior art. These features are not inherent in the materials taught in the cited references.

The limit of a magnetic moment larger than 1.7 teslas is a patentable feature. Numeric limits can serve as a basis for patentability. In re Glaug, 283 F.3d 1335, 62 USPQ2d 1151 (Fed. Cir. 2002):

While the measurement of a physical property may not of itself impart patentability to otherwise unpatentable claims, when the measured property serves to point up the distinction from the prior art, or advantages over the prior art, that property is relevant to patentability, and its numerical parameters can not only add precision to the claims but also may be considered, along with all the evidence, in determination of patentability.

## II.

Applicant met its burden of proof to show that prior art products do not necessarily or inherently possess characteristics of claimed products.

This burden was met by the applicant when the applicant submitted prior art Table 2.15, showing lack of inherency, with an amendment filed on January 4, 2005. This burden was again met by the applicant when the applicant submitted prior art Fig. 10.2(a)-(d) which showed lack of inherency with a Response filed on May 16, 2005.

Applicant twice met its burden of proof in showing that a magnetic moment greater than 1.7 teslas was not inherent in the art cited by the Examiner. The burden of proof shifted to the Examiner, and the Examiner did not produce any evidence to support

the assertion of inherency. The Examiner's making the rejections final was improper and should be reversed to provide applicant with either allowance of the claims or an opportunity to respond to a further non-final office action.

Conclusion

For the reasons advanced above, Appellant contends that each of the Claims on appeal is patentable. Therefore, reversal of all the rejections is requested.

Respectfully submitted,

WESTMAN, CHAMPLIN & KELLY, P.A.

By: 

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Appendix A

1. (original) A magnetic recording medium for communication with a transducer moving relative to the recording medium along a line of relative transducer motion, comprising:

- a substrate having a substrate surface;
- a seed layer disposed on the substrate surface;
- a soft magnetic underlayer disposed on the seed layer, the soft magnetic underlayer comprising a magnetic material having a magnetic moment larger than 1.7 Teslas, the soft magnetic underlayer having a texture that provides a magnetic easy axis that has an easy axis alignment parallel to the line of relative transducer motion; and
- a magnetic storage layer disposed on the soft magnetic underlayer.

2. (original) The magnetic recording medium of Claim 1 further comprising a second seed layer deposited on the soft magnetic underlayer, and a second soft magnetic underlayer deposited on the second seed layer, forming a multilayer laminated soft magnetic underlayer structure.

3. (original) The magnetic recording medium of Claim 1 wherein the recording medium comprises a disc, and the easy axis alignment is circumferential.

4. (original) The magnetic recording medium of Claim 1 wherein the recording medium comprises a drum, and the line of relative transducer motion and the easy axis alignment are circumferential.

5. (original) The magnetic recording medium of Claim 1 wherein the recording medium comprises a plate.

6. (original) The magnetic recording medium of Claim 1 wherein the soft magnetic underlayer is free of 90° and 180° domain walls.

7. (original) The magnetic recording medium of Claim 1 wherein the texturing maintains the easy axis alignment in the presence of an externally applied field.

8. (original) The magnetic recording medium of Claim 1 wherein the texture provides a magnetic hard axis that has a hard axis alignment that is to the line of relative transducer motion.

9. (original) The magnetic recording medium of Claim 1 wherein the seed layer comprises copper and has a concentrically textured seed layer surface that induces the texture of the soft magnetic underlayer.

10. (original) The magnetic recording medium of Claim 1 wherein the seed layer comprises a seed layer material selected to reduce coercivity  $H_c$  in the soft magnetic underlayer, the seed layer material being selected from the group: copper, ruthenium, permalloy, copper/iridium-manganese, and tantalum/copper.

11. (original) The magnetic recording medium of Claim 10 wherein an external magnetic field establishes the texture of the soft magnetic underlayer.

12. (original) The magnetic recording medium of Claim 1 wherein the magnetic material has a magnetic moment that is at least 2.0 teslas.

13. (original) The magnetic recording medium of Claim 1 wherein the magnetic material comprises Iron and Cobalt.

14. (original) The magnetic recording medium of Claim 13 wherein the magnetic material comprises about 65 at% Iron and 35 at% Cobalt.

15. (original) The magnetic recording medium of Claim 1 wherein the seed layer and the soft magnetic underlayer form a seeded double layer structure, and the seed layer has a thickness of about 5 nanometers and the soft magnetic underlayer has a thickness of about 50 nanometers.

16. (original) The magnetic recording medium of Claim 1 wherein the seed layer and the soft magnetic underlayer form a seeded double layer structure, and the seed layer has a thickness of about 5 nanometers and the soft magnetic underlayer has a laminated structure of about 50 nanometers thick soft magnetic films separated with non-magnetic spacers.

17. (original) The magnetic recording medium of Claim 1 wherein the seed layer and the soft magnetic underlayer form a seeded double layer structure, the soft magnetic underlayer is biased by an anti-ferromagnetic layer selected from the group of ruthenium and iridium-manganese.

18. (original) A method of manufacturing a magnetic recording medium for communication with a transducer moving relative to the recording medium along a line of relative transducer motion, comprising:

- providing a substrate having a substrate surface;
- depositing a seed layer on the substrate surface;
- depositing a soft magnetic underlayer on the seed layer, the soft magnetic underlayer comprising a magnetic material having a magnetic moment larger than 1.7 teslas, the

soft magnetic underlayer having a texture that provides a magnetic easy axis that has an easy axis alignment parallel to the line of relative transducer motion; and depositing a magnetic storage layer on the soft magnetic underlayer.

19. (original) The method of Claim 18 further comprising shaping the substrate into a disc aligning the easy axis in a circumferential direction on the disc.

20. (original) The method of Claim 18 further comprising shaping the substrate into a drum, and aligning the easy axis in a circumferential direction on the drum.

21. (original) The method of Claim 18 further comprising shaping the substrate into a plate.

22. (original) The method of Claim 18 further comprising forming the seed layer from copper and aligning a seed layer texture with the line of relative transducer motion.

23. (original) The method of Claim 18 further comprising selecting a seed layer material from the group: ruthenium, permalloy and tantalum-copper to reduce coercivity  $H_c$  in the soft magnetic underlayer.

24. (original) The method of Claim 23 further comprising applying an external magnetic field to establishes the texture of the soft magnetic underlayer.

25. (original) The method of Claim 18 further comprising selecting the magnetic material to have a magnetic moment that is at least 2.0 teslas.

26. (original) The method of Claim 18 further comprising selecting the magnetic material to comprise Iron and Cobalt.

27. (original) The method of Claim 18 wherein the magnetic material comprises about 65 at% Iron and 35 at% Cobalt.

28. (original) The method of Claim 18 wherein the seed layer and the soft magnetic underlayer form a seeded double layer structure, and the seed layer has a thickness of about 5 nanometers and the soft magnetic underlayer has a thickness of about 50 nanometers.

29. (withdrawn) A magnetic recording medium for communication with a transducer moving relative to the recording medium along a line of relative transducer motion, comprising:

- a substrate, a seed layer disposed on the substrate; a soft magnetic underlayer disposed on the seed layer, the soft magnetic underlayer comprising a magnetic material having a magnetic moment larger than 1.7 teslas, and a magnetic storage layer disposed on the soft magnetic underlayer; and

- means for texturing the soft magnetic underlayer to provide a magnetic easy axis that has an easy axis alignment parallel to the line of relative transducer motion.

30. (withdrawn) The magnetic recording medium of Claim 29 wherein the recording medium comprises a disc, and the easy axis alignment is circumferential.

31. (withdrawn) The magnetic recording medium of Claim 29 wherein the seed layer comprises copper and has a concentrically textured

seed layer surface that induces the texture of the soft magnetic underlayer.

32. (withdrawn) The magnetic recording medium of Claim 29 wherein the magnetic material has a magnetic moment that is at least 2.0 teslas.

33. (withdrawn) The magnetic recording medium of Claim 29 wherein the magnetic material comprises Iron and Cobalt.

**B. D. CULLITY**  
University of Notre Dame

# INTRODUCTION TO MAGNETIC MATERIALS

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## INDUCED MAGNETIC ANISOTROPY

### 10.1 INTRODUCTION

So far in this book we have encountered three kinds of magnetic anisotropy: crystal, shape, and stress. Various other kinds may be induced in certain materials, chiefly solid solutions, by appropriate treatments. These induced anisotropies are of considerable interest both to the physicist, for the light they throw on basic magnetic phenomena, and to the technologist, who may wish to exploit them in the design of magnetic materials for specific applications.

The following treatments can induce magnetic anisotropy:

1. *Magnetic annealing.* This means heat treatment in a magnetic field, sometimes called a *thermomagnetic* treatment. This treatment can induce anisotropy in certain alloys. (Here the term "alloys" includes not only metallic alloys but also mixed ferrites.) The results depend on the kind of alloy:
  - a) Two-phase alloys. Here the cause of anisotropy is the shape anisotropy of one of the phases and is therefore not basically new. However, it is industrially important because it affects the behavior of some of the Alnico permanent-magnet alloys. It will be described in Chapter 14.
  - b) Single-phase solid-solution alloys. Here it will be convenient to discuss substitutional and interstitial alloys in separate sections.
2. *Stress annealing.* This means heat treatment of a material that is simultaneously subjected to an applied stress.
3. *Plastic deformation.* This can cause anisotropy both in solid solutions and in pure metals, but by quite different mechanisms.
4. *Magnetic irradiation.* This means irradiation with high-energy particles in a magnetic field.

### 10.2 MAGNETIC ANNEALING (SUBSTITUTIONAL SOLID SOLUTIONS)

When certain alloys are heat treated in a magnetic field and then cooled to room temperature, they develop a permanent uniaxial anisotropy with the easy axis parallel to the direction of the field during heat treatment. They are then magnetically softer along this axis than they were before treatment. The heat treat-

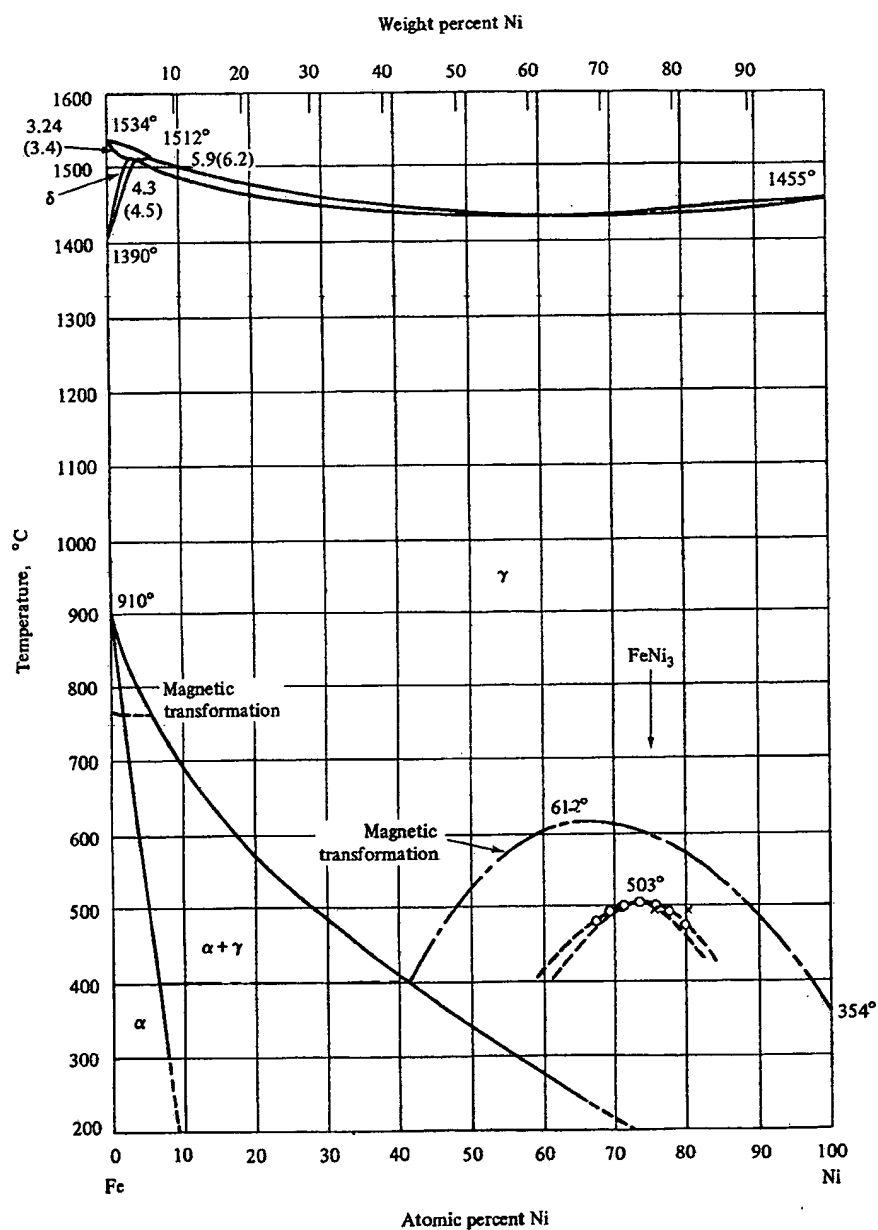


Fig. 10.1 Equilibrium diagram of Fe-Ni alloys. Hansen and Anderko [10.6].

ment may consist only of cooling through a certain temperature range in a field, rather than prolonged annealing; the cooling range or annealing temperature must be below the Curie point of the material and yet high enough, usually above

400 C, so that substantial atomic diffusion can occur. An alternating or unidirectional field is equally effective; all the field does is determine an easy axis, rather than direction, of easy magnetization. The field must be large enough to saturate the specimen during the magnetic anneal, if the resulting anisotropy is to develop to its maximum extent. Usually a field of some 10 Oe or less is sufficient; the material is magnetically soft to begin with, and its permeability at the magnetic-annealing temperature is higher than at room temperature. The term "magnetic annealing" is applied both to the treatment itself and to the phenomenon which occurs during the treatment; i.e., an alloy is often said to magnetically anneal if it develops a magnetic anisotropy during such an anneal. The subject of magnetic annealing has been reviewed by Graham [10.1]; Słonczewski [10.2]; and Chikazumi and Graham [10.3]; Graham's review contains a large bibliography classified by material composition.

The phenomenon of magnetic annealing was first discovered in 1913 by Pender and Jones [10.4] in an alloy of Fe + 3.5 percent Si. They found that cooling the alloy from about 800°C to room temperature in an alternating field, of about 20 Oe maximum value, caused a substantial increase in maximum permeability. Many years later Goertz [10.5] made measurements on a picture-frame single crystal, with  $\langle 100 \rangle$  sides, of an alloy of Fe + 6.5 percent Si; heat treatment in a field increased its maximum permeability from 50,000 to  $3.8 \times 10^6$ , the highest value yet reported for any material.

However, most of the research on magnetic annealing has been devoted to the binary and ternary alloys of Fe, Co, and Ni. Compositions which respond well to magnetic annealing are Fe + 65–85 percent Ni, Co + 30–85 percent Ni, Fe + 45–60 percent Co, and the ternary alloys containing 20–60 percent Ni, 15–35 percent Fe, balance Co. Magnetic annealing has been studied most often in binary Fe-Ni alloys, for which the equilibrium diagram is shown in Fig. 10.1. Both the  $\alpha$  (body-centered cubic) and the  $\gamma$  (face-centered cubic) phases are ferromagnetic. There is a large thermal hysteresis in the  $\alpha \rightarrow \gamma$  and  $\gamma \rightarrow \alpha$  transformations because of low diffusion rates below about 500 C, and the equilibrium shown in Fig. 10.1 is very difficult to achieve. For example, the  $\gamma \rightarrow \alpha$  transformation on cooling is so sluggish that it is easy to obtain 100 percent  $\gamma$  at room temperature in alloys containing more than about 35 percent Ni by air cooling  $\gamma$  from an elevated temperature. Hansen and Anderko [10.6] should be consulted for further details.

Typical of the magnetic-annealing results obtained on Fe-Ni alloys are those shown for 65 Permalloy in Fig. 10.2. Comparison of the hysteresis loop of (c) with (a) or (b) shows the dramatic effect of field annealing: the sides of the loop become essentially vertical, as expected for a material with a single easy axis. Conversely, if the loop is measured parallel to the hard axis, i.e., at right angles to the annealing field, the sheared-over, almost linear loop shown in (d) is obtained, where the change in the  $H$  scale should be noted. [Specimens for magnetic annealing studies are sometimes in the form of rods, either straight or made into a hollow rectangle in order to have a closed magnetic circuit. In any case it is not usually practical to apply a field transverse to the rod axis because of the very large demagnetizing factor, equal to  $2\pi$ , in that direction. Instead, a direct cur-

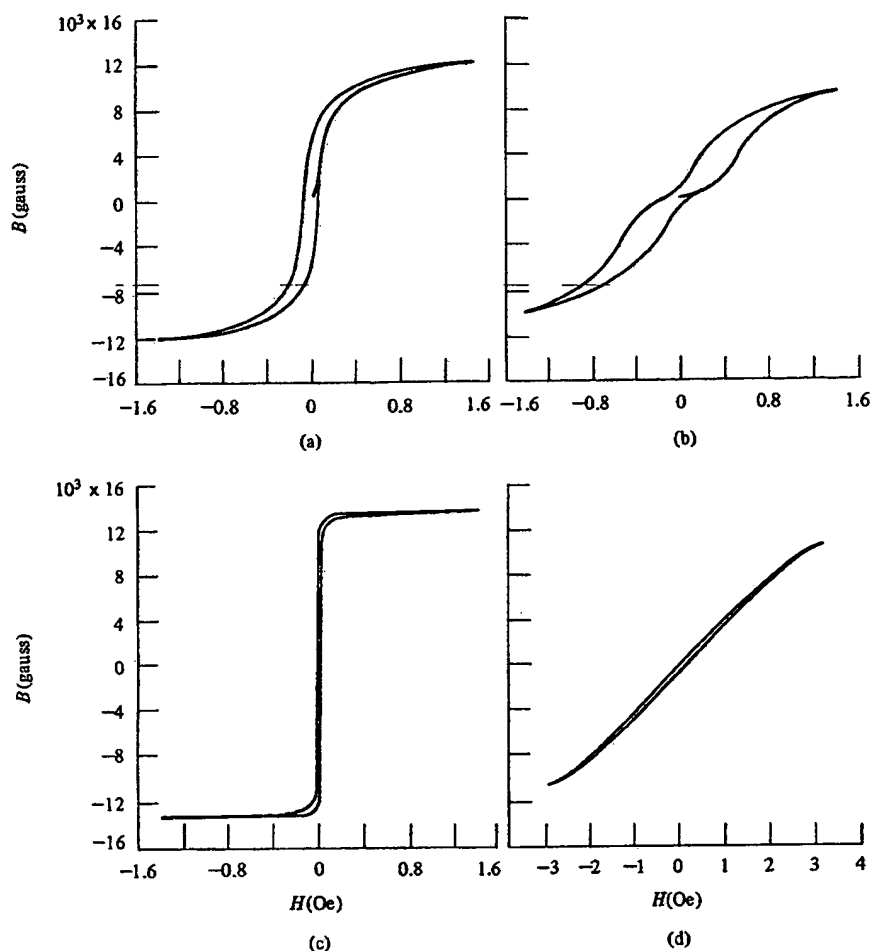


Fig. 10.2 Hysteresis loops of a 65 Ni-35 Fe alloy after various heat treatments: (a) annealed at 1000° C and cooled quickly, (b) annealed at 425° C or cooled slowly from 1000° C, (c) annealed at 1000° C and cooled in a longitudinal field, (d) same as (c) but with a transverse field. Bozorth [G.4].

rent is passed along the rod axis during the anneal, producing a circular field around the axis (Section 1.6). This field can easily be made strong enough to saturate the specimen circumferentially, except for a relatively small volume near the axis. If a magnetic measurement is subsequently made parallel to the axis in the usual way, the measurement direction is then at right angles to that of the annealing field. A longitudinal annealing field is achieved simply by wrapping the rod with a helical magnetizing winding, suitably protected by an insulator that will withstand the annealing temperature. If the specimen is in the form

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**gauss** (*Phys*) CGS electromagnetic unit of magnetic flux density; equal to  $1 \text{ maxwell cm}^{-2}$ , each unit magnetic pole terminating  $4\pi$  lines. Now replaced by the SI unit of magnetic flux density, the tesla (T).  $1 \text{ T} = 10^4 \text{ gauss}$ .

**oersted** (*Phys*) CGS electromagnetic unit of magnetic field strength, such that  $2\pi$  oersted is a field at the centre of a circular coil one centimetre in radius carrying a current of one abampere (10 A). Now replaced by the SI unit  $\text{A m}^{-1}$ .  $1 \text{ A m}^{-1} = 4\pi \times 10^{-3} \text{ oersted}$ .

**tesla** (*Phys*) SI unit of magnetic flux density or magnetic induction equal to  $1 \text{ weber m}^{-2}$ . Equivalently, the magnetic induction for which the maximum force it produces on a current of unit strength is 1 N. Symbol T.

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**Magnetic moment** The relationship between a magnetic field and the torque exerted on a magnet, a current loop, or a charge that is moving in the field.

When a magnet is placed in a magnetic field of strength  $H$ , there is a torque  $L$  exerted on the magnet by the field. The torque is a maximum when the axis of the magnet is perpendicular to the field. The ratio of the torque for this position to the strength of the field is called the magnetic moment  $M$  of the magnet. See MAGNET.

If a flat coil of wire of  $N$  turns and area  $A$ , in which there is a current  $I$ , is placed in a magnetic field of flux density  $B$ , the coil experiences a torque  $L$  given by Eq. (1), where  $\theta$  is the

$$L = NIAB \sin \theta \quad (1)$$

angle between the field and the normal to the plane of the coil. The torque is maximum when  $\theta = 90^\circ$ , that is, when the plane of the coil is parallel to the field. The ratio of the maximum torque to the flux density  $B$  is the magnetic moment of the coil, as shown in Eq. (2). If a charge is spinning, there is a

$$M = \frac{L}{B} = NIA \quad (2)$$

charge in motion and thus an electric current. The spin is equivalent to a tiny current loop which has a magnetic moment. Atomic nuclei also possess magnetic moments. See ELECTRON MAGNETIC MOMENT; ELECTRON SPIN; NUCLEAR MOMENTS.

[K.V.M.]

# **Magnetic Disk Drive Technology**

*Heads, Media,  
Channel,  
Interfaces,  
and Integration*

**Kanu G. Ashar**

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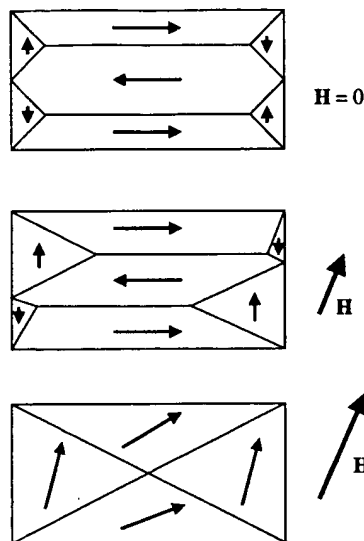


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## 2.15 DOMAINS

Now that we understand anisotropy, we can discuss the hysteresis loop behavior in more detail. A typical magnetic material will in general consist of many *magnetic domains*. A *domain* is a local region of the material in which all atomic moments are pointing in the same direction. However, the moment in one domain will not be parallel to the moment in a neighboring domain. For example, in the upper part of Figure 2.19 we show the directions of magnetization in a rectangular slab of material.



**Figure 2.19** Wall motion and domain rotation under application of an external magnetic field.

Each arrow shows the magnetization direction in a particular domain. The lines between domains represent *domain walls*. These walls are very narrow regions—in iron, they are approximately 100 nm (1000 Å) thick—in which the magnetization changes from its direction in one domain to its direction in the adjacent domain. Thus, the magnetization in a magnetic material does not change directions gradually over large distances. The changes in magnetization direction are confined to the very small volume of the material consisting of domain walls.

We have assumed in Figure 2.19 that this material has a uniaxial anisotropy with a horizontal easy axis. Why is not all the magnetization in this figure directed horizontally? The pattern of domains in the top of Figure 2.19 is a particular arrangement that minimizes demagnetizing energy. We saw in our earlier discussion of demagnetizing fields that when the magnetic moment is pointing toward a boundary where the magnetization changes, such as at the edge of the sample, uncompensated magnetic poles appear. These poles create a magnetic field, and this field contains energy. To reduce the demagnetizing energy, the domains try to

arrange themselves in such a way as to reduce the number of these poles. In this figure, we note that at all edges of the sample, the magnetization is parallel to the edge. Therefore, no poles are created at the edges. We also note that all magnetization vectors intersect domain walls at the same angle ( $45^\circ$ ). Thus, the perpendicular components of magnetization on entering and leaving a domain wall are equal, and so there is no net magnetic charge built up at a domain wall. The particular magnetization configuration shown in the figure results in no magnetostatic energy being created by demagnetizing poles on surfaces or on domain walls. Therefore, it is a low-energy configuration.

If a field is applied as shown in the figure, the domain magnetization tries to line up with the field (like the dipole in Fig. 2.7). The first thing that happens is the domain walls begin to move. With very small fields, domains may move reversibly since they sit in small potential wells. This reversible region is shown as the 0-*a* section on the initial hysteresis loop of Figure 2.13. At higher applied fields, as in the middle panel of Figure 2.19, the domains move irreversibly in such a way as to enlarge the domains that are favorably oriented with respect to the field and diminish the domains that are unfavorably oriented. This corresponds to the section *a-b* on the initial hysteresis curve of Figure 2.13. Finally, at large fields, rotation of the domains occurs and domain rotation is reversible (section *b-c* of Fig. 2.13). At a still higher field, all the magnetization points in the field direction, there are no more domain walls, and the sample is said to be saturated ( $\mathbf{M} = \mathbf{M}_s$  in Fig. 2.13).

How much magnetization switching is due to wall motion and how much is due to domain rotation depends upon the field orientation. If  $\mathbf{H}$  is oriented parallel to the easy axis direction, the sample switches entirely by wall motion. If  $\mathbf{H}$  is oriented perpendicular to the easy axis, the sample switches entirely by domain rotation. For intermediate fields, the sample switches by a combination of wall motion and domain rotation.

## 2.16 EXCHANGE

We have discussed that in certain materials like iron and nickel, atomic magnetic dipoles tend to line up with each other to produce an overall magnetization for the material. Materials in which adjacent dipole moments tend to line up in the same direction are called *ferromagnetic*. The occurrence of ferromagnetism is relatively rare—looking at the periodic table, we see that only a few of the pure elements (iron, nickel, cobalt, and gadolinium; see Table 2.1) exhibit ferromagnetism at room temperature. Without this tendency for atomic dipoles to line up parallel to each other, we would not have magnetic recordings, or electric motors, or many of the devices to which we have grown accustomed.

The tendency for neighboring atomic dipoles to line up parallel or antiparallel to each other is called *exchange*. The detailed description of exchange can be given only in terms of quantum mechanics. Basically, exchange results from the overlap of orbiting electrons on adjacent atoms. The atomic moment of an atom is

# Electronics Designers' Handbook

*Second Edition*

*First Edition by*

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## Notes to Table 2.15.

1. The units indicated apply to the quantity tabulated when the values in the column are divided by the common factor, if any, shown at the column heading. Properties are mostly compiled from the following sources:

- (a) Richard M. Bozorth, *Ferromagnetism*, D. Van Nostrand Company, Inc., Princeton, N.J., 1951.
- (b) R. Ochsenfeld and K. H. v. Klitzing, *Magnetische Werkstoffe*, sec. 445, pp. 737-843 of group 6, vol. IV, part 3, Landolt-Börnstein, *Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik*, Ernst Schmidt (ed.), Springer-Verlag OHG, Berlin, 1957.
- (c) Commercial literature.

Data as tabulated are for materials at room temperature (about 25°C).

2. For significance of American Iron and Steel Institute (AISI) designations, see ASTM A 345-55, Standard Specifications for Flat-Rolled Electrical Steel, pp. 73-76 of part 8, 1973 *Annual Book of ASTM Standards*, American Society for Testing and Materials, Philadelphia, 1973. Weight percentages are indicated with the balance as iron. —

3. For optimum magnetic properties the materials must be carefully heat-treated after fabrication. This generally involves annealing in a controlled atmosphere ( $N_2$  = nitrogen,  $H_2$  = hydrogen) and controlled cooling ( $Q$  = quenching,  $C$  = controlled cooling rate) frequently in the presence of a magnetic field.

4. Above the Curie temperature the material no longer exhibits residual magnetic polarization.

5. For measurement method see ASTM B 193-722, Standard Method of Test for Resistivity of Electrical Conductor Materials, pp. 227-232 of part 8, *op. cit.*

6. Standard methods of measurement are described in part 8, 1973 *Annual Book of ASTM Standards*, *op. cit.* See also Raymond L. Sanford and Irvin L. Cooter, Basic Magnetic Quantities and the Measurement of the Magnetic Properties of Materials, National Bureau of Standards Monograph 47, May 21, 1962, pp. 439-476 of *NBS Spec. Publ. 300*, vol. 3, Precision Measurement and Calibration, U.S. Government Printing Office, Washington, D.C., December 1968.

For large values of  $H_p$ , the hysteresis loop energy depends in a complex manner on  $H_p$ , material, and geometry. In 1892, C. P. Steinmetz developed an empirical relation for hysteresis loop energy.<sup>1</sup>

$$\frac{W_h}{V} = \eta_s B_p^n \quad (2.41)$$

This relation with the Steinmetz constant  $\eta_s$ , joules per cubic meter tesla<sup>n</sup>, and the exponent adjusted for a best fit, is useful if measurement or graphical data are not available.

As the magnetic field is varied, voltages are induced in the magnetic materials that produce eddy currents and associated  $I^2R$  eddy current losses. If the magnetic core consists of cylindrical rods of radius  $R_0$ , oriented axially with respect to the magnetic field, then the per unit volume eddy current power loss is

$$\frac{P_e}{V} = \frac{\sigma R_0^2}{8} \left[ \frac{dB(t)}{dt} \right]^2 \Rightarrow \frac{\sigma}{16} (\omega R_0 B_p)^2 \quad (2.42)$$

where  $\sigma$  is the conductivity of the magnetic material. The second result is applicable when the flux density (assumed uniform throughout the cross section) is sinusoidal,  $B(t) = B_p \sin \omega t$ . Similarly if the magnetic core consists of laminations of thickness  $X_r$  and width  $X_w$  oriented longitudinally with respect to the magnetic field, then provided the laminations (conductivity  $\sigma$ ) are electrically insulated from each other the per unit volume eddy current power loss is

$$\frac{P_e}{V} = \frac{\sigma X_r^2}{16[1 + (X_r/X_w)^2]} \left[ \frac{dB(t)}{dt} \right]^2 \Rightarrow \frac{\sigma (\omega X_r B_p)^2}{32[1 + (X_r/X_w)^2]} \quad (2.43)$$

This result<sup>2</sup> takes into account the eddy current both along the width and across the thickness of the laminations. For  $X_r/X_w < 1$ ,  $P_e/V$  in Eq. (2.43) is independent of  $X_w$ . For a general symmetrically cyclically magnetized condition the net per unit volume

<sup>1</sup> C. P. Steinmetz, On the Law of Hysteresis, *Trans. AIEE*, vol. 9, pp. 3-51, January 1892.

<sup>2</sup> S. S. Attwood, *Electric and Magnetic Fields*, p. 358, John Wiley & Sons, Inc., New York, 1949.

TABLE 2.15 Properties of Soft Ferromagnetic Magnetic Materials (Note 1)\*

No.	Material	Description (Note 2)	Density $\rho$ , kg/m <sup>3</sup>	Thermal conductivity $\lambda$ , W/(K m)	Coefficient of linear thermal expansion, $\alpha_{\text{av}}$ , $\times 10^6$ , (K) <sup>-1</sup>	Tensile strength, $S \times 10^{-8}$ , N/m <sup>2</sup>	Tensile modulus, $E$ , $\times 10^{10}$ , N/m <sup>2</sup>	(Melt. temp.) (Anneal. temp.), $^{\circ}\text{C}$ (Note 3)	Curie temp. $T_c$ , $^{\circ}\text{C}$ (Note 4)	Resistivity $\rho$ , $\Omega\text{m}$ (Note 5)
1	Iron, Fe	0.9995 Fe, body-centered cubic single crystal	7,880	78	11.7	5.4-6.2	21.14	1539 1482 H <sub>2</sub> + 880	770	$1.0 \times 10^{-7}$
2	Iron, Fe	99.8% Fe	7,880	78	11.7	5.4-6.2	21.14	1536.5 950	770	$1.0 \times 10^{-7}$
3	Iron, Fe	Mild steel, 0.2% C	7,859	78	11.7	3.1		1523 950	770	$1.0 \times 10^{-7}$
4	Nickel, Ni	99% Ni, face-centered cubic single crystal	8,902	89	12.8	5.0-9.0	19.95	1453 1000	358	$7.06 \times 10^{-8}$
5	Cobalt, Co	99% Co, hexagonal single crystal	8,850	97	12	2.6-7.5		1492 1000	1115	$5.86 \times 10^{-8}$
6	Silicon-iron	3% Si, cube on edge	7,650	18.0		$\parallel 3.0$ $\perp 3.0$	$\parallel 11$ $\perp 11$	1488 800 N <sub>2</sub>	740	$4.7 \times 10^{-7}$
7	Silicon-iron	3% Si, oriented, Silectron, AISI Grade M-5	7,650	18.0		$\parallel 3.0$ $\perp 3.2$	$\parallel 11$ $\perp 19$	1488 800 N <sub>2</sub>	740	$4.7 \times 10^{-7}$
8	Silicon-iron	3% Si, oriented, Silectron, AISI Grade M-6	7,650	18.0		$\parallel 3.0$ $\perp 3.2$	$\parallel 11$ $\perp 19$	1488 800 N <sub>2</sub>	740	$4.5 \times 10^{-7}$
9	Silicon-iron	3% Si, oriented, Silectron, AISI Grade M-7	7,650	18.0		$\parallel 3.0$ $\perp 3.2$	$\parallel 11$ $\perp 19$	1488 800 N <sub>2</sub>	740	$4.7 \times 10^{-7}$
10	Silicon-iron	2.85 to 3.25% Si, Trans. C nonoriented, AISI Grade M-19	7,550	16.3		4.0-4.2	0.63	1488 870 N <sub>2</sub>	732	$5.4 \times 10^{-7}$
11	Silicon-iron	2.7 to 3.1% Si, Dynamo Special non-oriented, AISI Grade M-22	7,650	18.0		3.9-4.1		1488 870 N <sub>2</sub>	732	$4.6 \times 10^{-7}$
12	Silicon-iron	2.5 to 2.9% Si, Dynamo Grade non-oriented, AISI Grade M-27	7,650	19.7		3.7-3.8		1480 870 N <sub>2</sub>	732	$4.5 \times 10^{-7}$
13	Silicon-iron	1.7 to 2.3% Si, Electrical Grade non-oriented, AISI Grade M-36	7,750	30.5		3.4-3.5		1506 870 N <sub>2</sub>	735	$3.7 \times 10^{-7}$
14	Silicon-iron	1.5 to 2.0% Si, Armature Grade non-oriented, AISI Grade M-43	7,750	40.6		3.2-3.3		1510 870 N <sub>2</sub>	737	$2.8 \times 10^{-7}$
15	Silicon-iron	2.25% Si, Relay Grade 5 nonoriented	7,650		11.6	5.3		1502 1000 H <sub>2</sub>	749	$4.0 \times 10^{-7}$

16	Steel	1% C	7,830	45.1	12.4	13.8	1465 870 N <sub>2</sub> 1536 1100 1515	770	$1.2 \times 10^{-7}$
17	Aluminum-iron	3.5% Al	7,460					750	$5.5 \times 10^{-7}$
18	Aluminum-iron	13% Al, Alfer	6,660			4.8	1515	510	$9.0 \times 10^{-7}$
19	Aluminum-iron	16% Al, Alperm	6,500			6.1	1500 600 Q	400	$1.4 \times 10^{-6}$
20	Nickel-iron	30% Ni, Thermoperm		11.0	3.4		1460 1000 1450	417	
21	Nickel-iron	36% Ni, Hyperm 36	8,150	1.0	0.88	4.8		417	$6.5 \times 10^{-7}$
22	Nickel-iron	45% Ni, 45-Permalloy	8,170	15.9	8.4	5.0	1440 1050	480	$4.5 \times 10^{-7}$
23	Nickel-iron	50% Ni, Hipernik	8,250	15.5	9.5	5.0	1438 1200 H <sub>2</sub>	500	$4.5 \times 10^{-7}$
24	Nickel-iron	50% Ni, Deltamax	8,250	15.5	8.4	4.4	1438 1075 H <sub>2</sub> + C	500	$4.5 \times 10^{-7}$
25	Nickel-iron	50% Ni, 50-Isoperm	8,250	15.5	9.0	4.0	1438 1100	500	$4.0 \times 10^{-7}$
26	Nickel-iron	78.5% Ni, 78-Permalloy	8,600		12.5	4.8	1440 1050 + 600 Q	600	$1.6 \times 10^{-7}$
27	Cobalt-iron	50% Co, Permendur	8,300		11.0		1485 800	980	$4.0 \times 10^{-7}$
28	Molybdenum-iron	3% Mo, Moly-Iron	7,900		11.5	3.0		805	$2.0 \times 10^{-7}$
29	Sendust	10% Si + 5% Al	8,800				As cast	500	$6.0 \times 10^{-7}$
30	36 Isoperm	36% Ni + 9% Cu	8,200					300	$7.0 \times 10^{-7}$
31	Radio-Metal	45% Ni + 5% Cu	8,300				1050	530	$5.5 \times 10^{-7}$
32	Sinimax	43% Ni + 3% Si	7,700				1125 H <sub>2</sub>		$8.5 \times 10^{-7}$
33	Monimax	48% Ni + 3% Mo	8,270				1125 H <sub>2</sub>	400	$8.0 \times 10^{-7}$
34	45-25 Perminvar	45% Ni + 25% Co					1000 + 400	715	$1.9 \times 10^{-7}$

\* Notes appear on page 2-97.

TABLE 2.15 Properties of Soft Ferromagnetic Magnetic Materials (continued)

No.	Material	Description (Note 2)	Density $\rho$ , kg/m <sup>3</sup>	Coeffi- cient of linear thermal expansion, $\alpha_{\Delta T}$ $\times 10^6$ , (K) <sup>-1</sup>		Thermal conduc- tivity $\lambda$ , W/(K m)	Tensile strength, $S \times 10^{-4}$ , N/m <sup>2</sup>	Tensile modulus, $E_T \times 10^{-10}$ , N/m <sup>2</sup>	(Melt. temp., Anneal. temp.), °C (Note 3)	Curie temp. $T_C$ , °C (Note 4)	Resis- tivity $\rho$ , $\Omega$ m (Note 5)
35	Megaperm 6510	65% Ni + 10% Mn									$5.8 \times 10^{-7}$
36	7-70 Perminvar	70% Ni + 7% Co	8,600						$1000 + 425$	650	$1.6 \times 10^{-7}$
37	Cr-Permalloy	78.5% Ni + 3.8% Cr	8,500						1000	420	$6.5 \times 10^{-7}$
38	4-79 Permalloy	79% Ni + 4% Mo	8,740			4.4	17.2		$1100 H_s + C$	460	$5.5 \times 10^{-7}$
39	Supermalloy	79% Ni + 5% Mo	8,770						$1300 H_s + C$	400	$6.0 \times 10^{-7}$
40	Superperminvar	22.8% Co + 9% Ni							Low temp.		
41	Hiperco	35% Co + 0.5% Cr	8,000						1490	970	$2.0 \times 10^{-7}$
42	Vanadium Permendur	49% Co + 2% V	8,150	9.2		6.2	24.1		850	980	$4.0 \times 10^{-7}$
43	Mumetal	77% Ni + 5% Cu + 2% Cr	8,580	12.5		4.4	17.2		1485 840 $N_s$	400	$6.2 \times 10^{-7}$
44	Superpermalloy	78.1% Ni + 2.9% Cr + 2.5% Sn							$1175 H_s + C$		$6.1 \times 10^{-7}$
45	1040	72% Ni + 14% Cu + 3% Mo	8,760						$1100 H_s$	290	$5.6 \times 10^{-7}$

TABLE 2.15 Properties of Soft Ferromagnetic Magnetic Materials (continued)

No.	Initial relative permeability $\kappa_{rel}$ (Note 6)	Maximum relative permeability $\kappa_{rel, max}$ (Note 6)	$H_0$ (H at $\mu_{max}$ ), A/m (Note 6)	$B_0$ (B at $\mu_{max}$ ), teslas (Note 6)	$H_m$ A/m (Note 6)	$B_m$ teslas (Note 6)	Retentivity $M_{re}$ , teslas (Note 6)	Coercivity $H_{cr}$ , A/m (Note 6)	$-(B_d H_d)_{max}$ , J/m <sup>3</sup>	Rayleigh constant $\eta_R$ , H/A	Steinmetz constant $\eta_{St}$ , J/(m <sup>3</sup> T <sup>-1</sup> )	Steinmetz exponent $n$	Hysteresis loop energy $W_h$ , J/m <sup>3</sup>
1	1.0 × 10 <sup>4</sup>	[100] 2.9 × 10 <sup>5</sup> [110] 2.1 × 10 <sup>5</sup> [111] 1.8 × 10 <sup>5</sup>	5.5	[100] 1.97 [110] 1.45 [111] 1.22	[100] 13.5 [110] 47.8 [111] 43.8 7 × 10 <sup>4</sup>	2.158	1.6	4	5.6	3.14 × 10 <sup>-3</sup>	300	1.6	30
2	150	5 × 10 <sup>3</sup>				2.15		79.5		3.14 × 10 <sup>-3</sup>			500
3	120	2 × 10 <sup>3</sup>	280	0.70	[111] 4 × 10 <sup>3</sup> [110] 2 × 10 <sup>4</sup>	2.12	0.72	143	500	3.14 × 10 <sup>-3</sup>			500
4	220	[111] 645 [110] 530 [100] 380	520	[111] 0.42 [110] 0.35 [100] 0.25	[100] 2.8 × 10 <sup>4</sup> [0001] 1.5 × 10 <sup>5</sup> [1010] 8.0 × 10 <sup>5</sup>	0.62	0.3	56		3.90 × 10 <sup>-6</sup>			200
5	[0001] 70 [1010] 3	[0001] 250 [1010] 3	[0001] 4.8 × 10 <sup>3</sup> [1010] 7.9 × 10 <sup>4</sup>	[0001] 1.5 [1010] 0.3	[0001] 1.5 × 10 <sup>5</sup> [1010] 8.0 × 10 <sup>5</sup>	1.79		797		1.62 × 10 <sup>-7</sup>			200
6	[115 × 10 <sup>3</sup> 1.5 × 10 <sup>3</sup>	[5.0 × 10 <sup>4</sup> 1.5 × 10 <sup>4</sup>	14.3 14.3	0.9 0.9	[1.95 × 10 <sup>4</sup> 1.95 × 10 <sup>4</sup>	2.00 2.00	1.5 1.5						
7	1.5 × 10 <sup>3</sup>	[5.0 × 10 <sup>4</sup> 4.7 × 10 <sup>4</sup>	14.3 15.2	0.9 0.9	[7.16 × 10 <sup>3</sup> 3.96 × 10 <sup>4</sup>	1.97 1.96	1.4 0.72						
8	350					2.01							
9						1.96							
10	300	7.2 × 10 <sup>3</sup>	71.5	0.63	3.96 × 10 <sup>4</sup>	1.97	0.730	43	10.5	2.4 × 10 <sup>-3</sup>			160
11	290	6.6 × 10 <sup>3</sup>	79.6	0.66	3.18 × 10 <sup>4</sup>	1.97	0.730	43	11.5				
12	290	6.0 × 10 <sup>3</sup>	87.5	0.65	3.42 × 10 <sup>4</sup>	1.98	0.735	43	11.5				
13	280	5.5 × 10 <sup>3</sup>	119	0.82	3.34 × 10 <sup>4</sup>	1.99	0.903	56	18.5				
14	280	5.0 × 10 <sup>3</sup>	127	0.80	3.74 × 10 <sup>4</sup>	2.03	0.880	72	21.0				
15	15	6.7 × 10 <sup>3</sup>	107	0.90	3.58 × 10 <sup>4</sup>	2.04	0.860	61	21.0				
16	200	3.8 × 10 <sup>3</sup>	157	0.75	5.0 × 10 <sup>4</sup>	2.00	0.95	600	1.4	1.6 × 10 <sup>3</sup>			
17	500	1.9 × 10 <sup>4</sup>				1.90		24					
18	700	3.7 × 10 <sup>3</sup>				1.20		53					
19	3.0 × 10 <sup>3</sup>	5.5 × 10 <sup>4</sup>				0.80		3.2					
20						0.20							
21	2.5 × 10 <sup>3</sup>	2.0 × 10 <sup>4</sup>				1.3		8					
22	2.5 × 10 <sup>3</sup>	2.5 × 10 <sup>4</sup>				1.6		23.9		2.52 × 10 <sup>-4</sup>			120
23	4.0 × 10 <sup>3</sup>	7.0 × 10 <sup>4</sup>	3.5	0.32	4.0 × 10 <sup>3</sup>	1.6	1.45	4.0					22
24	500	1.5 × 10 <sup>5</sup>	3.4	0.53	800	1.55	0.95	5.5	8.2	1.38 × 10 <sup>-3</sup>	13	1.77	33
25	90	100				1.60		480					
26	8.0 × 10 <sup>3</sup>	1.0 × 10 <sup>5</sup>	480	1.2	8.0 × 10 <sup>3</sup>	1.08		4.0					58
27	800	5.0 × 10 <sup>3</sup>	126	0.98	3.3 × 10 <sup>4</sup>	2.45	1.6	160					1.2 × 10 <sup>3</sup>
28		6.0 × 10 <sup>3</sup>				2.07	1.17	60.5					426

TABLE 2.15 Properties of Soft Ferromagnetic Magnetic Materials (concluded)

No.	Initial relative perme- ability $\kappa_{rel}$ (Note 6)	Maximum relative perme- ability $\kappa_{rel, max}$ (Note 6)	$H_0$ ( $H$ at $\mu_{max}$ ), A/m (Note 6)	$B_0$ ( $B$ at $\mu_{max}$ ), teslas (Note 6)	$H_{50}$ A/m (Note 6)	$B_{50}$ teslas (Note 6)	Reten- tivity $M_{re}$ teslas (Note 6)	Coer- civity $H_{cr}$ A/m (Note 6)	$-(B_d H_d)_{max}$ J/m <sup>3</sup>	Ray- leigh con- stant $\eta_R$ , H/A	Stein- metz con- stant $\eta_s$ , J/(m <sup>3</sup> T <sup>1/2</sup> )	Stein- metz expo- nent $n$	Hys- teris- is loop energy $W_p/k$ , J/m <sup>3</sup>
29	$3.0 \times 10^4$	$1.2 \times 10^5$				1.00		4.0					10
30	60	65						478					110
31	$2.0 \times 10^3$	$2.0 \times 10^4$				1.56	0.4	31.8					40
32	$3.0 \times 10^3$	$3.5 \times 10^4$				1.1	0.55	7.9					80
33	$2.0 \times 10^3$	$7.5 \times 10^4$	12.3	0.54		1.45	0.89	7.9				1.9	250
34	400	$2.0 \times 10^3$	6.0	0.55	$5.6 \times 10^3$	1.55		95.6		$1.6 \times 10^{-3}$			
35	$4.8 \times 10^3$	$2.6 \times 10^4$	320	0.8		0.86		6.4					
36	850	$4.0 \times 10^3$	7.3	0.24		1.25		4.8					
37	$1.2 \times 10^4$	$6.2 \times 10^4$			800	0.80		4.0					
38	$2.0 \times 10^4$	$3.3 \times 10^5$	0.7	0.28	$1.4 \times 10^3$	0.87	0.65	4.0	2.08	$5.4 \times 10^{-3}$	17.6	1.9	20
39	$1.0 \times 10^3$	$1.0 \times 10^4$	0.32	0.40		0.79	0.45	0.16		0.188			0.8
40	63.5												
41	650	$1.0 \times 10^4$				2.42		80					330
42	800	$8.0 \times 10^3$	129	1.4	$8.0 \times 10^4$	2.4	2.14	25	56		224	3.6	600
43	$2.0 \times 10^4$	$2.9 \times 10^5$	0.64	0.24		0.65	0.32	4.0	1.42		44	1.9	4.0
44	$2.4 \times 10^4$	$8.0 \times 10^4$											
45	$4.0 \times 10^4$	$1.0 \times 10^5$	1.8	0.23	80	0.6	0.24	1.6					20

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